SRTM Topography

Update: Includes NASA Version 3.0 (SRTM Plus)

1.0 Introduction

The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA - previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60-meter long baseline (Kobrick, 2006). A description of the SRTM mission can be found in Farr and Kobrick (2000) and Farr et al. (2007), and radar interferometry is explained in Rosen et al. (2000)

Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. The length of the acquired swaths ranges from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take."

SRTM was the primary (and virtually only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected within a 222.4-hour period. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending, or south-going, orbit passes) to fill in areas shadowed from the radar beam by terrain.

This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. The coverage reaches somewhat further north than south because the side-looking radar looked toward the north side of the Shuttle.

NASA Version 3.0 SRTM (SRTM Plus) data includes topographic data from non-SRTM sources to fill the gaps ("voids") in earlier versions of SRTM data. The primary fill data are from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor on NASA's Terra satellite, which has imaged Earth stereoscopically in near infrared wavelengths since 1999 (Yamaguchi et al., 1998; Fujisada et al., 2011). The secondary fill is mostly USGS GMTED2010 elevation data (Global Multi-resolution Terrain Elevation Data), which are lower resolution and derived from many sources (Danielson and Gesch, 2011). The USGS National Elevation Dataset (NED) (Gesch et al., 2002) was used instead of GMTED2010 for the United States (except Alaska) and northernmost Mexico.

2.0 Data Set Characteristics

2.1 Versioning

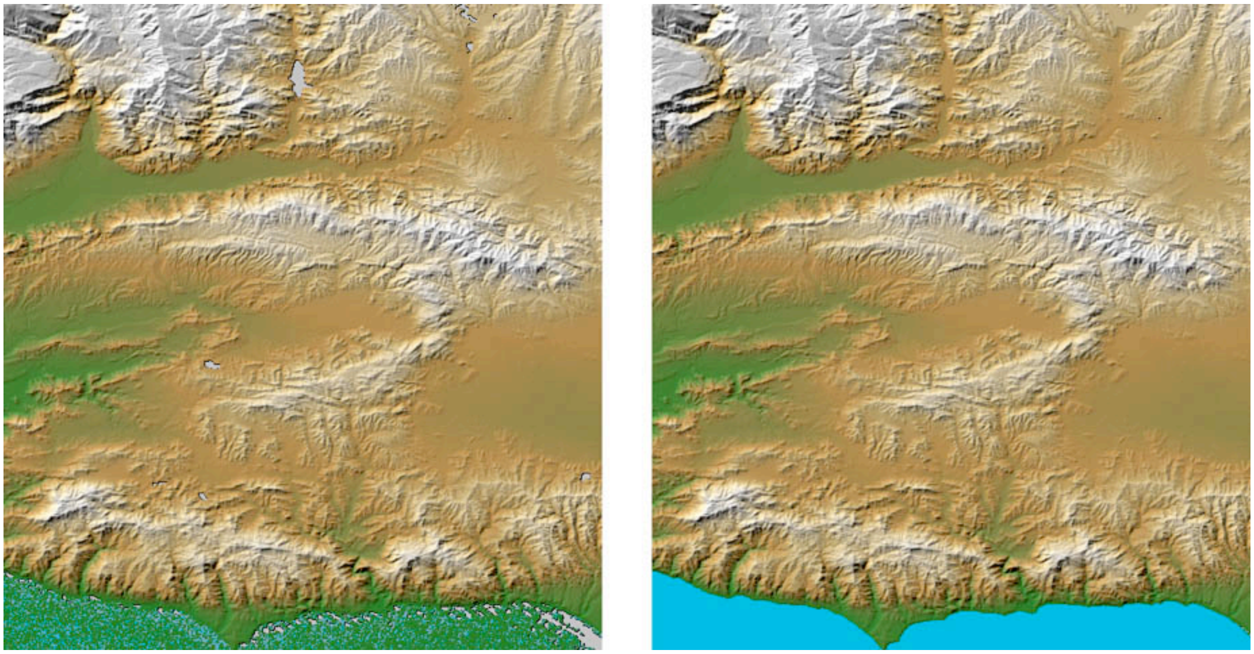
SRTM data have undergone a sequence of processing steps resulting in data versions that have different characteristics. All processing has occurred at one-arc-second (about 30 meters) postings. Three-arc-second (about 90 meters) data are freely available for worldwide coverage. One-arc-second data coverage is freely available for only the United States and its territories.

Version 1.0: SRTM radar echo data were processed in a systematic fashion using the SRTM Ground Data Processing System (GDPS) supercomputer system at the NASA Jet Propulsion Laboratory. This processor transformed the radar echoes into strips of digital elevation data, one strip for each of the 1000 or so data swaths. These strips were eventually mosaicked into 14,278 one degree by one degree tiles. The data were processed on a continent-by-continent basis beginning with North America and proceeding through South America, Eurasia, Africa, Australia and Islands, with data from each continent undergoing a “block adjustment” to reduce residual errors. The data were arranged in SRTM format, detailed in Section 3 below, and made available online from the USGS as Version 1.0.

Each SRTM data tile contains a mosaic and blending of elevations generated by averaging all data takes that fall within that tile. Since the primary error source in synthetic aperture radar data is speckle, which has the characteristics of random noise, combining data through averaging reduced the error by the square root of the number of data takes used. SRTM data takes ranged from a minimum of one (about 5% of the coverage) up to as many as 24 (very little of the coverage). Typical coverage was 2-3 data takes.

Version 2.1: Next, NGA applied several post-processing procedures to the SRTM data including editing, spike and pit removal, water body leveling and coastline definition. Following these "finishing" steps data were returned to NASA for distribution to the scientific and civil user communities as well as the public. These data are referred to as Version 2.0. Version 2.1 corrects some minor errors found in the original Version 2.0 three-arc-second product. Figure 1 shows a portion of tile N34W119.hgt, demonstrating the difference between the edited (Version 1.0) and unedited (Version 2.0) data.

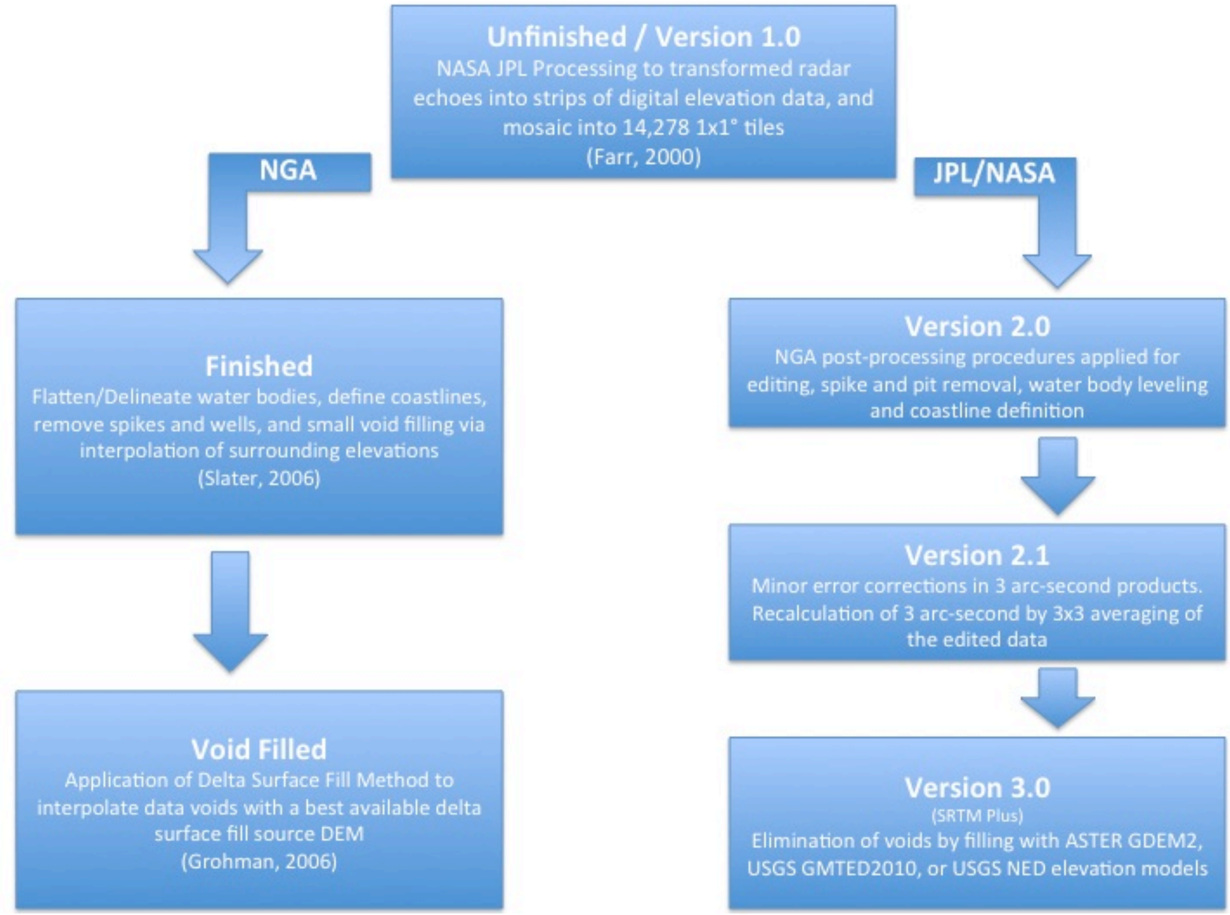
FIGURE 1
N34W119 – Malibu Coast and Simi Valley, California
Ocean (bottom) and small lakes (e.g., center top) are flattened with shoreline elevations.



Version 1.0 – Unedited Version 2.1 - Edited

Version 3.0: Elimination of the voids in the SRTM DEM was the primary goal of a project under the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) Program. Ultimately this was achieved by filling the voids with elevation data primarily from the ASTER GDEM2 (Global Digital Elevation Model Version 2) and secondarily from the USGS GMTED2010 elevation model or the USGS National Elevation Dataset (NED). Figure 2 shows the SRTM Genealogy, demonstrating the different agencies and processing techniques applied to the original SRTM V1.0 data.

FIGURE 2 – SRTM Genealogy



The Sensor Information Laboratory Corporation of Japan used more than one million ASTER scenes to produce GDEM2 (Fujisada et al., 2012). (ASTER is a joint project of NASA and Japan's Ministry of Economy, Trade and Industry, and now, Japan Space Systems.) At its best, GDEM2 is comparable to full resolution SRTM elevation data, but it is much less consistent in quality. This is primarily due to ASTER being an optical system. Clouds can obscure its views. (SRTM, a radar system, looked through clouds.) Both ASTER and SRTM can have difficulty in very steep and rugged terrain, but ASTER has some advantage there due to its more nadir view (the stereo pair includes a nadir view). Thus, ASTER DEMs can generally fill SRTM voids in rugged terrain that is not too often obscured by clouds. Elsewhere, both sensors have difficulty in smooth, flat terrain such as desert sand sheets, where little of the SRTM radar signal was reflected back to the Shuttle, and where ASTER stereoscopy is hindered by the lack of Earth surface patterns to correlate between the two views.

GDEM2 is void-free, but it does not consist entirely of ASTER elevation measurements. Some areas in GDEM2 consist of USA or Canadian national elevation data sets, or SRTM three-arc-second data, or NGA elevation data from undisclosed sources. Meanwhile, some GDEM2

ASTER elevations (where the alternative sources were not available) are cloud tops that are hundreds (or even thousands) of meters above the ground surface. Fortunately, most GDEM2 coverage does not have these problems in the extreme (but some does).

GDEM2 was merged with SRTM by retaining all of the SRTM Version 2.1 data and using a modified Delta Surface Fill algorithm (Grohman et al., 2006) to fill just the voids. This is essentially a “rubbersheet” methodology in which GDEM is matched to SRTM vertically and gently warped to meet the SRTM void edges seamlessly. Another technique was developed to detect significant errors in GDEM2, based upon its inconsistency with SRTM, and to reintroduce voids at those locations. These new voids were then filled with GMTED2010 or NED data.

GMTED2010 was used at its finest level of spatial detail, 7.5 arc-seconds, but was interpolated to one-arc-second postings to blend with the SRTM DEM that was partially filled with GDEM2. Again, a modified Delta Surface Fill algorithm was used to fill the remaining voids with GMTED2010, but NED was used instead of GMTED2010 for the United States (except Alaska) plus northernmost Mexico (north of 25 degrees north latitude).

Ancillary one-byte (0 to 255) “NUM” (number) files were produced for SRTM NASA Version 3.0. These files have names corresponding to the elevation files, except with the extension “.NUM” (such as N37W105.NUM). The elevation files use the extension “.HGT”, meaning height (such as N37W105.HGT). The separate NUM file indicates the source of each DEM pixel, and the number of ASTER scenes used (up to 100), if ASTER, and the number of SRTM data takes (up to 24), if SRTM. The NUM file for both three-arc-second products (whether sampled or averaged) references the 3x3 center pixel. Note that NUMs less than 6 are water and those greater than 10 are land.

1 = Water-masked SRTM void *
2 = Water-masked SRTM non-void *
5 = GDEM elevation = 0 in SRTM void (helped fix ocean masking)
11 = NGA-interpolated SRTM (were very small voids in SRTMv1)
21 = GMTED2010 oversampled from 7.5 arc-second postings
25 = SRTM within GDEM **
31 = NGA fill of SRTM via GDEM***
51 = USGS NED (National Elevation Dataset)
52 = USGS NED via GDEM
53 = Alaska USGS NED via GDEM
72 = Canada CDED via GDEM (Canadian Digital Elevation Data)
101-200 = ASTER scene count (count limited to 100)
201-224 = SRTM swath count (non-voided swaths) Actual maximum = 24

* Water-masked in SRTMv2 by NGA using its SRTM Water Body Database (SWBD). (NGA: National Geospatial-Intelligence Agency).

** GDEM used SRTM 3-arc-second data, oversampled to 1-arc-second postings, as fill at some locations. Rarely some of these interpolations are at locations of void within the original 1-arc-second SRTM.
*** GDEM used a version of SRTM supplied by NGA that included elevation measurements from undisclosed sources.

2.2 Processing Steps
All Version 3.0 processing occurred at the original 1-arc-second postings. Products released at 3 arc-seconds were derived from the final 1-arc-second DEM. Version 3.0 processing steps are as follows:

<u>1-2: Prepare GMTED2010</u>
(1) GMTED2010 was found to have geo-location errors in much of Africa (and vicinity) and parts of South America. It was determined that these correspond to the SPOT DEM inputs to GMTED2010, and they consist of one full GMTED2010 pixel (7.5 arc-seconds) shift to the southwest (for Africa) or east (for South America) for some 1x1-degree latitude-longitude quads. The fix consisted of shifting those quads into proper position and interpolating the consequent pixel-wide gaps at the trailing edge.

(2) GMTED2010 was then resampled to 1-arc-second postings by bicubic interpolation to match the full-resolution SRTMv2 and GDEM2. Bicubic interpolation can introduce artifacts in some topographic features such as sea cliffs and mesas, including the introduction of some elevation values outside the range of the input pixel values (i.e. extrapolation). But in general, bicubic interpolation was found to produce far fewer artifacts than bilinear interpolation.

<u>3: Use GDEM2 to edit the SRTM water mask</u>
(3) SRTM voids were filled with an elevation of 0 if the pixel has an elevation of 0 in GDEM2. This was found to greatly improve the topographic representation of shorelines, especially near sea cliffs by avoiding interpolations across voids that overlap steep coastal mountains (or high terraces) and flat offshore water, where there should be a topographic inflection at the shoreline.

<u>4-6: Apply a modified Delta Surface Fill method to fill SRTM voids with GDEM2</u>
(4) Subtract SRTM elevations from GDEM2 elevations, but retain the SRTM voids (that remain after Step 3). This is the GDEM2-SRTM delta surface.

(5) Fill the GDEM2-SRTM delta surface voids mostly via iterative edge-growing interpolation: In each iteration, each void pixel that borders any non-void pixel is interpolated from the nearest non-void pixels in each of 16 directions (north, south, east, west, northwest, southwest, northeast, southeast, and the eight directions intermediate to those eight: NNE, ENE, ESE, SSE, SSW, WSW, WNW, NNW). Each of the 16 reference pixels is weighted by the inverse square root of its distance. The effect of the inverse square root is to most heavily weight the closest pixels but to minimize the influence of distance variations for the more distant reference pixels. In other words, close pixels are most important in the interpolation and their relative closeness

matters, while far pixels are less important in the interpolation and their relative distance does not matter (much). This edge-growing interpolation is applied in 50 iterations. The iterations greatly help to smooth the interpolation because the reference pixels in each successive step were themselves interpolated in the previous step. Note that delta surfaces of DEMs are entirely noise (i.e., errors of some sort) in either SRTM or GDEM or both. The goal here is to characterize the broader systematic differences between the DEMs without being too subject to the higher spatial frequency random errors. Thus, smoothing is important for the interpolation. After 50 iterations, the smaller voids are already filled. Meanwhile, for the larger voids, the high spatial frequency random errors along the void edges are largely suppressed, such that any remaining void pixels can be filled in one last step (no edge growing) via a final interpolation applied to all remaining void pixels. The delta surface is now complete (void free).

(6) Subtract the delta surface from GDEM2. The result is the original SRTM DEM, where it already existed, with its voids filled by GDEM2, which has been adjusted in height and by gentle warping to merge seamlessly with SRTM.

SRTM Non-Void Areas	= GDEM2 – (GDEM2 – SRTM)
	= SRTM
SRTM Void Areas	= GDEM2 – (filled (GDEM2 – SRTM))
	= GDEM2 with adjustments to fit SRTM

7: Use the Delta Surface itself as an error check for GDEM2 quality

(7) The DEM is now spatially complete, but is it accurate? If we assume that the original SRTM DEM is accurate, then the delta surface measures probable errors in the void fills. If GDEM2 exactly matched SRTM then the delta surface would be all zeroes, and the interpolated voids would also (of course) be all zeroes. Any differences from zero indicate an error that is assumed to be in GDEM2 (although that is not always true). These do not affect the final DEM where SRTM is not void since SRTM is used (unchanged) in the final DEM. However, large values in the delta surface (+/- differing from zero) indicate a significant inconsistency between SRTM and GDEM2, such as a cloud elevation in GDEM2. Much experimentation was used to determine an optimum threshold for rejecting some void fills as errors. A threshold of 80 meters was found to catch most obvious errors while minimizing the rejection of apparently good elevation values. Using this threshold, voids were reintroduced to the GDEM2-filled SRTM DEM where the delta surface was equal to or outside +/-80 meters. Note again that this is only in original SRTM voids and is often only part(s), if any, of each void.

8: Fill remaining voids with GMTED2010 or NED

(8) Repeat Steps 4-6 (above) using GMTED2010 instead of GDEM2, and using the DEM from Step 7 (above) instead of SRTM. This is a (modified) Delta Surface Fill of the rejected parts of the GDEM fill of SRTM.

NED, instead of GMTED2010, was used in the 48 conterminous United States and northernmost Mexico (N25-29W65-125) plus Hawaii (N19-23W154-161).

The final DEM is now complete: SRTM is filled with GDEM2, except where they are discordant, and GMTED2010 or NED is used to fill those areas.

2.3 One-arc-second (“30 meter”) and three-arc-second (“90 meter”) postings

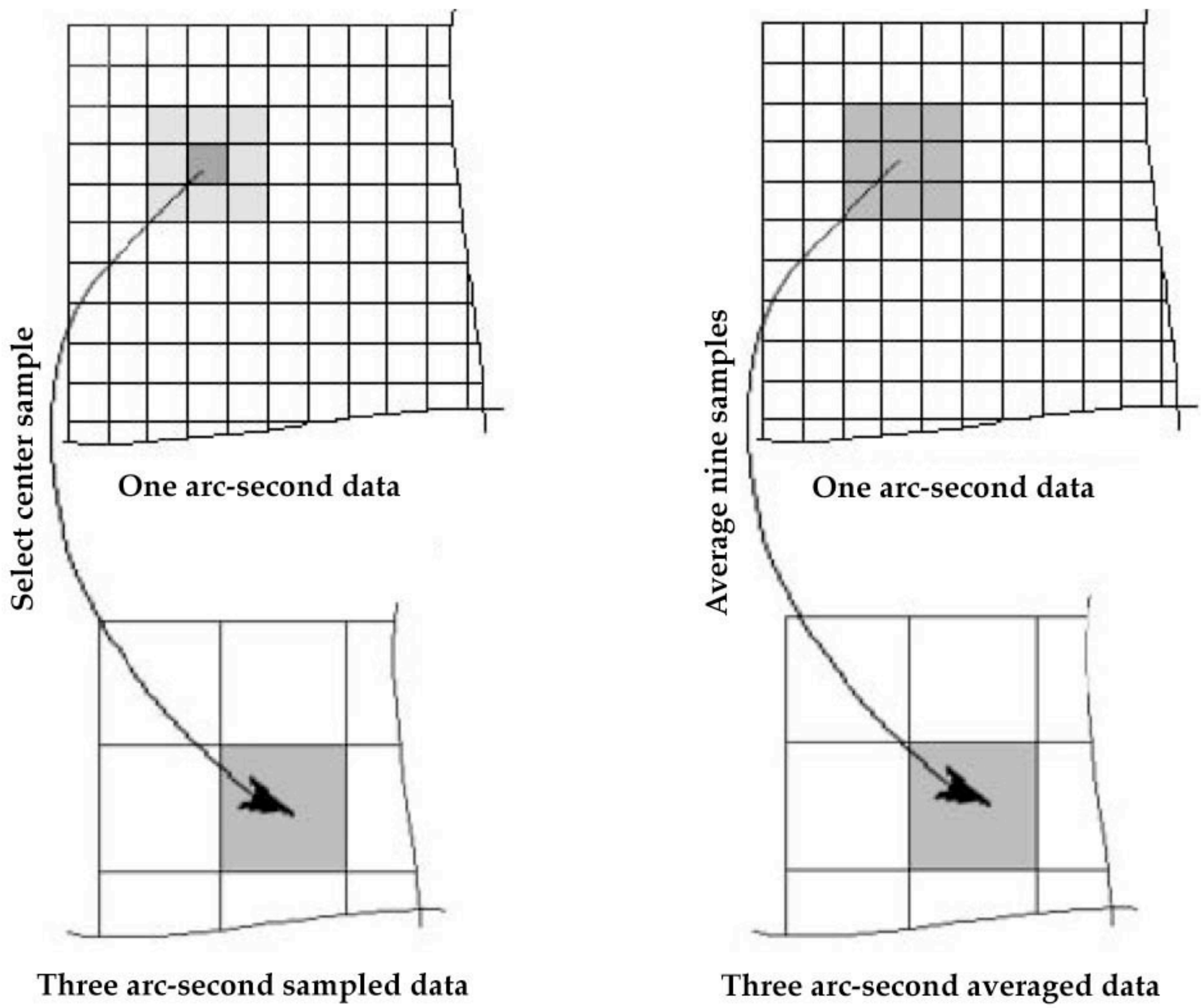
SRTM data are organized into individual rasterized tiles each covering one-degree of latitude by one-degree of longitude. Sample spacing for individual data points is either 1 arc-second (USA and territories) or 3 arc-seconds (worldwide), referred to as SRTM1 and SRTM3, respectively. Since one arc-second at the equator corresponds to roughly 30 meters in horizontal extent, the SRTM1 and SRTM3 are sometimes referred to as "30 meter" or "90 meter" data. (Note: a void-free 30-arc-second (about one kilometer) Version 1.0 product, referred to as SRTM*30 was also produced, with voids filled with the GTOPO30 elevation model.) With postings of 1, 3, and 30 arc-seconds, corresponding to nominal postings at 30, 90, and 1000 meters, and with versions numbering 1, 2, and 3, users should take care to reference these data specifically by “arc-seconds” or “meters” as well as by “version.”

For Version 2.1, there is a difference between the data distributed via download from the Land Processes Distributed Active Archive Center (LPDAAC), and those available from the Earth Resources Observations and Science (EROS) Center through the Long Term Archive (LTA). Three-arc-second sampled data from the LTA have been generated from the one arc-second data by “sampling”. In this method, each three-arc-second data point is generated by selecting the center sample of the 3x3 array of one-arc-second points that surround the post location. For the LPDAAC three-arc-second data each point is the average of the nine (3x3) one-arc-second samples surrounding the post, as illustrated in Figure 3.

It is felt by many analysts that the averaging method produces a superior product by decreasing the high frequency ‘noise’ that is characteristic of radar-derived elevation data. This is similar to the conventional technique of ‘taking looks’, or averaging pixels in radar images to decrease the effects of speckle and increase radiometric accuracy, although at some cost of horizontal resolution. The true spatial resolution of SRTM one-arc-second data is generally estimated to be in the range of 50-80 meters. Thus the one-arc-second postings (beneficially) oversample the data. Three-arc-second postings derived by sampling exclude some detail. Three-arc-second postings derived by averaging use all the original postings but, in effect, blur them. The bottom line is that the sampled three-arc-second data has a slightly finer spatial resolution (about 100 meters), but with more noise, in comparison to the averaged three-arc-second data, which has a slightly courser spatial resolution (about 112 meters), but with less noise.

For Version 3.0, three-arc-second data were derived using the sampling method and also the averaging method, and each is available for download.

FIGURE 3
Deriving 3 arc-second data from 1 arc-second data: Sampling Method versus Averaging Method.



3.0 Data Formats

The names of individual data tiles refer to the latitude and longitude of the southwest (lower left) corner of the tile. For example, N37W105 has its lower left corner at 37 degrees north latitude and 105 degrees west longitude and covers (slightly more than) the area 37-38˚N and 104-105˚W. To be more exact, the file name coordinates refer to the geometric center of the lower left pixel, and all edge pixels of the tile are centered on full-degree lines of latitude and/or longitude.

SRTM*1 data are sampled at one arc-second of latitude and longitude and each file contains 3601 lines and 3601 samples. The rows at the north and south edges as well as the columns at the east and west edges of each tile overlap (and are identical to) the edge rows and columns in the adjacent tile. SRTM*3 data are sampled at three arc-seconds and contain 1201 lines and 1201 samples with similar overlapping rows and columns.

The data are in "geographic" projection (also known as equirectangular or plate carrée), which is to say a raster presentation with equal intervals of latitude and longitude in the vertical and horizontal dimensions, respectively. More technically, the projection maps meridians to vertical straight lines of constant spacing, and circles of latitude (“parallels”) to horizontal straight lines of constant spacing. More simply, this might be thought of as no projection at all, but simply a latitude-longitude data array.

Height files have the extension .HGT, and the DEM is provided as two-byte (16-bit) binary signed integer raster data. Two-byte signed integers can range from -32767 to 32767 meters and thus can encompass the range of elevations found on Earth. There are no header or trailer bytes embedded in the file. The data are stored in row major order, meaning all the data for the northernmost row (row 1) are followed by all the data for row 2, etc.

All elevations are in meters referenced to the WGS84/EGM96 geoid (NGA, 1997; Lemoine, 1998).

The two-byte data are in Motorola "big-endian" order with the most significant byte first. Most PCs and Macintosh computers built after 2006 use Intel ("little-endian") order so byte swapping may be necessary. Some software performs the swapping during ingest.

Voids in Versions 1.0 and 2.1 are flagged with the value -32768. There are no voids in Version 3.0.

4.0 References

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5.0 Web sites of interest:

SRTM Project:
http://www2.jpl.nasa.gov/srtm/

ASTER Project:
http://asterweb.jpl.nasa.gov/

GMTED2010:
https://lta.cr.usgs.gov/GMTED2010

National Elevation Dataset (NED):
http://ned.usgs.gov/